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Edited by
LTC KARL FRIEDL
HARRIS LIEBERMAN, PhD
DONNA H. RYAN, MD
and
GEORGE A. BRAY, MD

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HARRIS R. LIEBERMAN and BRYAN P. COFFEY

Preliminary Finding from a New Device for Monitoring Performance and Environmental Factors in the Field

ABSTRACT

The ability to assess mental and physical performance, in an automated and minimally intrusive manner, is critical for the conduct of military field studies and applied research in nutrition, neuroscience, and environmental and occupational medicine. Technologies that are currently available for automated field assessment of performance are limited, and commercially available methods for ambulatory monitoring, such as the activity monitor (actigraph), do not directly assess any aspect of performance. This paper will introduce a new device, the U.S. Army Research Institute of Environmental Medicine vigilance monitor, which was developed for assessment of human performance in an automated, continuous manner in the field. The monitor has evolved from the actigraph and from microcomputer-based tests of cognitive function. The device continuously monitors and records certain aspects of human performance and, like the actigraph, patterns of activity of the wearer. The device assesses vigilance and reaction time by presenting auditory stimuli and by assessing the wearer's responses. In addition, the USARIEM vigilance monitor continuously assesses a variety of environmental conditions that are of relevance to the mental and physical performance and health of the wearer such as: ambient illumination, sound, and temperature. The device is small enough to be worn on the wrist or belt and, like the actigraph, is completely self-contained, requiring no external input to perform all of its functions for several days. Preliminary data from several military field studies employing the device will be presented, and some of the implications of this new assessment technology will be discussed.

Introduction

The advances in microelectronics, sensors, and microcomputers that have had many significant consequences for our society have had relatively little impact on the ability of scientists to assess human behavior and performance in noninvasive, unobtrusive ways. Assessment technologies that could be employed as individuals go about their daily activities would be of great value in research on military performance and in many other applied settings. One of the few devices that is currently available and capable of monitoring human behavior in ambulatory, free-living individuals in the field is the activity monitor or actigraph. This device measures minute-by-minute patterns of spontaneous motor activity and has been used in numerous studies of healthy individuals, including soldiers in the field, and patients with various diseases. However, activity monitors usually assess just a single parameter, that is, physical activity, and do not provide direct information on any aspect of mental or physical performance. Assessing key aspects of performance is critical for military and other field studies.

This chapter will introduce a new technology that has evolved from the actigraph and from modern microcomputer-based tests of cognitive function. Initially, we will address some issues concerning assessment of cognitive performance, particularly in the field. Then the technology of actigraphy, and some of its military field applications, will be discussed. Finally, the U.S. Army Research Institute of Environmental Medicine (USARIEM) vigilance monitor, a new device designed for ambulatory assessment of a variety of behavioral and environmental factors will be described. Preliminary data from several studies employing this device will be presented.

Problems Associated with Assessment of Human Cognitive Performance in the Field

Standard laboratory tests of cognitive performance involve using paper and pencil to fill out forms, taking computerized tests, or using mechanical devices such as pegboards. These tests measure functions such as learning, memory, reaction time, vigilance, attention, manual dexterity, and sensory function. Using such assessment technologies, a wide range of human behaviors can be measured and, at least in theory, related to real world performance. Scientists conducting research in this area rely on such tests to assess performance, but there are numerous problems associated with employing them, not only in the field, but also in the laboratory. One limitation is that it is usually necessary for the subject being tested to stop all ongoing activities to participate. When the subjects in a study are soldiers engaged in training exercises or other military operations this is a significant problem and often causes cognitive testing to be excluded from field studies. Studies of nutritional, environmental, or other factors must be minimally intrusive with regard to use of soldiers' time. When field research is conducted with military units, commanders generally impose significant limitations on the amount of time their soldiers will be available to investigators.

Another problem often associated with behavioral testing in the field is circadian variation in performance (1). Because of such variation, to fully describe the daily pattern of any behavioral parameter, testing must be conducted at multiple times during the day. Alternatively, if testing is to take place once a day, the test session must be conducted at the same time. It is not appropriate to compare data collected at one time of day with data collected at another time. In field studies with military units, as opposed to laboratory studies, the necessity of testing at the same time of day can be impractical and often significantly increases the extent of disruption produced by investigators (2).

Another key issue is uncertainty regarding the underlying behavioral function a test actually assesses. Almost all behavioral tests, even the simplest, require the subject to use a variety of sensory systems, information processing capabilities, and motor functions. For example, visual choice reaction time requires: the visual system to process sensory information, attentional functions to focus on the critical sensory parameters, memory functions to choose the correct stimulus, and decision-making processes to determine whether to initiate a response. The motor system is required to make even the simplest response. Therefore, we cannot always accurately define the limiting or key factor that a cognitive test assesses. Also, under different environmental conditions or due to the presence of some extraneous influence on performance, the critical factor in any behavioral test may change. For example, in a cold environment where substantial shivering is occurring, impaired ability of the subject to make the necessary motor responses may prevent assessment of the cognitive parameter the test is actually intended to monitor. These issues can be addressed when appropriate methods are carefully selected and employed effectively.

One particularly difficult issue in any study of performance is determining whether a test is optimal to address the research question of interest. It is difficult to determine what specific test or class of tests will be most appropriate to assess the effects of a particular experimental parameter. Selecting the correct test, particularly when only a few can be administered, as is almost always the case in field studies, presents a variety of problems. Often it is not known what test will be most sensitive to the effects of a nutrient, drug, or environmental condition on human performance. If the "wrong" test is selected, it will be insensitive to the treatment being evaluated. For example, for many years there was considerable controversy about whether moderate doses of caffeine, equivalent to those found in single servings of common foods, had effects on behavior (3). However, when appropriate tests of vigilance were employed, consistent effects of caffeine in this dose range were reliably observed (4, 5).

Another problem that is unique to field studies is that subjects are not accessible to the investigator for long periods of time. Military units frequently conduct operations in extreme and sometime dangerous environments. In many instances, it is not possible for investigators to follow along to administer tests. Frequently, these extreme environments are of the greatest interest in regard to performance. One solution to this problem is to issue hand-held computers to the soldiers participating in a study. They are then responsible for self-testing their own mental performance at designated times. This technique, in combination with conventional tests of cognitive function, was employed in a month-long field study conducted by USARIEM and the Natick Research and Development and Engineering Center (NRDEC) (6). However, there were considerable reliability problems with the hand-held computers in the field, and soldiers often were not able or willing to take the tests (7).

It is apparent from this brief review that the problems associated with behavioral testing are substantial and are magnified when testing must be conducted in the field. However, there may be unique and innovative solutions that can be employed to provide data on soldiers in the field as they go about their daily activities without interrupting training or other operations. The ability to continuously assess performance in the field with an ambulatory device similar to the activity monitor would overcome some of these obstacles to conducting high-quality field research.

Activity Monitoring—Field Applications

Activity monitors and other passive, electronic monitoring devices such as foot-strike monitors can be effectively used to collect behavioral data in the field (6, 8, 9). Although such devices currently do not assess mental performance, they can be employed to provide valuable information on soldiers conducting operations in the field. Activity monitors (or actigraphs) record minute-by-minute patterns of activity of the wearer (8, 10, 11, 12). Some of the most advanced versions are capable of recording data continuously for many days and are suitable for use in the field if appropriate precautions to prevent their damage by environmental conditions are taken (13). The greatest problem in using such devices in the field is insuring that they are water-resistant and are not accidentally immersed by test subjects.

One of the more sophisticated, commercially available activity monitors is manufactured by Precision Control Devices, Fort Walton Beach, Florida. The device, the Motionlogger Actigraph, model AMA-32, has been effectively employed to assess patterns of rest and activity and to estimate duration and fragmentation of sleep. The devices are 4 centimeters long, 3.1 centimenters wide, 1 centimeter high, and weigh 57 grams. They are typically worn on the wrist of the nonpreferred hand using a standard wristwatch band. Each device contains a microcomputer, 32 kilobytes of memory, an analog-to-digital converter, and a piezoelectric motion sensor. They are powered by standard wristwatch batteries. Data collected by the AMA-32 can be downloaded to a laptop or other IBM-compatible computer for further analysis using a specially developed computer program (ACTION 3, Ambulatory Monitoring, Inc., Ardsley, NY) or other software, such as a program developed by Sadeh and colleagues (14). The device and its predecessor were developed, in part, with support from the Army Medical Research, Development and Materiel Command. A similar actigraph is manufactured by Computer Science Applications, Fort Walton Beach, Florida. Another device, the Acitllume, manufactured by Ambulatory Monitoring, Inc., monitors light intensity levels in addition to activity. Actigraphs have been used successfully as a supplemental measure of energy expenditure in conjunction with other techniques in military field studies (15). Although the relationship between activity and energy expenditure is complex, activity monitoring can improve estimates of energy expenditure provided by other methods (15, 16).

The ability of actigraphs to predict sleep versus waking state of humans has been demonstrated by several investigators. Algorithms to classify activity patterns of individuals wearing activity monitors as representing a waking or sleeping state have been developed and validated (10, 14, 17). Actigraphs are widely employed to supplement the more accurate and detailed information provided on the extent and structure of sleep by polysomnography. They can also be employed to assess circadian rhythms of rest and activity in normal individuals and those with disturbed rhythms due to psychiatric illness or other medical conditions or transmeridional travel (11, 18, 19, 20, 21).

Recent studies have used actigraphs to assess various clinical conditions associated with disrupted sleep such as periodic leg movement syndrome (22), insomnia (23), and sleep in a mentally retarded individual (24). Activity monitors have also been employed to assess sleep in healthy elderly individuals (23), to monitor circadian rhythms in Alzheimer's disease (20), to clarify the relationship between physical activity and hypertension (25), and to study the effects of the antimalarial drug mefloquine on sleep (26). Not surprisingly, they have also been used to study small children with attention-deficit hyperactivity disorder (27).

Actigraphs have been of great value in both laboratory and field. For example, in a study recently conducted at USARIEM with the Ambulatory Monitoring, Inc.'s AMA-32 actigraphs, the effects of sleeping in a chemical protective mask on sleep quantity and quality were assessed (2). The monitors unequivocally documented that sleep was significantly degraded when soldiers slept in the Army's new chemical protective mask. The monitors demonstrated that total time spent sleeping was reduced and that sleep was frequently interrupted when volunteers wore the chemical protective mask at night. The results were consistent with a variety of other data collected during the study. Self-reported measures of sleep quality, mood, and next-day performance, assessed with computer-based tests, were all adversely affected by sleeping in the mask (2).

Activity monitors have also been employed in a number of nutrition research studies. One of the first studies to simultaneously evaluate patterns of rest/activity and food consumption/circadian rhythms in the same population was conducted at the Massachusetts Institute of Technology Clinical Research Center (11, 28, 29). That study, which utilized an early, relatively primitive activity monitor (30), documented significant changes in age-related patterns of activity and macronutrient intake, as well as differences in normal patterns of rest and activity in healthy young and elderly volunteers living in an identical environment.

More recently, we have employed more sophisticated monitors in a number of field studies designed to assess various aspects of military nutrition. One study evaluated a new field ration, the Unitized Group Ration (UGR), and also the effects of a supplemental carbohydrate beverage on a Marine heavy artillery unit conducting a live-fire training exercise in a hot desert environment (Hotson *et al.*, unpublished observations). Figure 1 presents raw data from one subject collected during that study with an AMA-32 activity monitor. The figure was generated by the ACTION III computer program and displays daily patterns of rest and activity over the several days of the study. In spite of temperatures as high as 45°C, subjects maintained a high level of activity on most days. Below the plots of the rest/activity pattern for each day are corresponding plots indicating the derived sleep versus waking state of the subject at any given moment in time. The estimates of sleep versus waking state are automatically generated by the Action III program using a validated algorithm (Fig. 1). Energy expenditure, as assessed by the doubly labeled water technique (31), was quite high (approximately 4100 kcal/day) and was consistent with the high levels of physical activity documented by the actigraphs (Hotson *et al.*, in preparation).

Activity monitors have also been used successfully in Army field studies conducted to assess the effects of administration of the hormone melatonin on sleep and performance. In a study conducted with an Army aviation unit traveling across multiple time zones, resynchronization of circadian rhythms of rest and activity was examined using activity monitors and computer-based tests of cognitive performance. Properly timed administration of melatonin accelerated adaptation to a new schedule as documented by both activity monitors and cognitive tests (21).

Generally, it appears that results from activity monitors and cognitive performance tests agree with regard to the nature of the effects observed. For example, in a study of ranger students in which both tech-

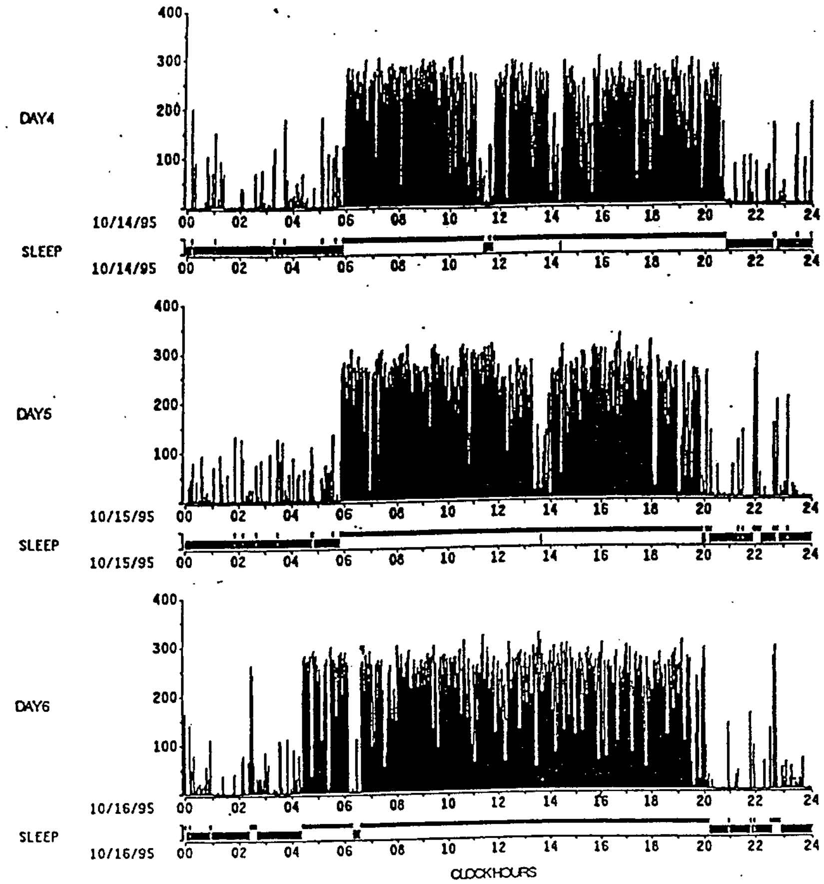

Figure 1. Daily patterns of rest and activity in a Marine volunteer wearing the AMA-32 activity monitor for three consecutive days. The volunteer was participating in a USARIEM nutrition field study in a hot desert environment (Hotson *et al.*, in preparation). Each vertical line plotted on the x-axis represents the summed total amount of movement emitted by the wearer in a one-minute period of time. Each individual activity plot is a bar that indicates a 24-hour period starting at 0000 hours on the indicated date. Below each plot is estimated sleep versus waking time. When a thicker bar appears next to the x-axis this indicates that the subject's activity is characteristic of sleep.

nologies were used, activity monitors documented significant loss of sleep while paper-and-pencil tests of performance found substantial degradation in mental function (13). In the study discussed above, which was conducted with army aviators, administration of melatonin improved sleep, as assessed indirectly with activity monitors, and cognitive function, as assessed with computer-based tests (21). In another study discussed above, where the effects of a chemical protective mask on sleep were evaluated, both sleep patterns and next-day performance were substantially disrupted by sleeping in the mask. It therefore appears that patterns of rest and activity as assessed by actigraphs can reflect either enhancement or decrements in performance documented by standardized tests of cognitive performance.

One clear advantage of activity monitors over traditional cognitive tests is that they provide continuous assessment of a form of behavior, in particular, physical activity. Although activity monitors cannot directly assess performance per se, the data they collect can be related to both the physical and the mental state.

The USARIEM Vigilance Monitor

As discussed above, activity monitors have been shown to be invaluable research tools in a wide variety of situations, including nutrition laboratory and field research, laboratory studies of sleep, studies of resynchronization following transmeridional travel, and clinical studies. However, they lack the capability of assessing performance directly. Therefore, in an effort to extend the technology of actigraphy, we have developed a new class of ambulatory monitoring devices that will provide additional capabilities to researchers interested in assessing behavior and performance in the field and laboratory. The devices are particularly suitable for studying soldiers as they conduct field exercises and actual operations, and may also have a number of civilian applications. The monitors have all the capabilities of actigraphs such as the AMA-32 and, in addition, can be used to assess and modify performance. Furthermore, due to rapid advances in microelectronics and sensor technologies, it was possible to include sensors for monitoring several environmental parameters in the device. The new monitors are intended to measure how certain nutritional and environmental variables influence mental performance and to evaluate the relationship between work performance

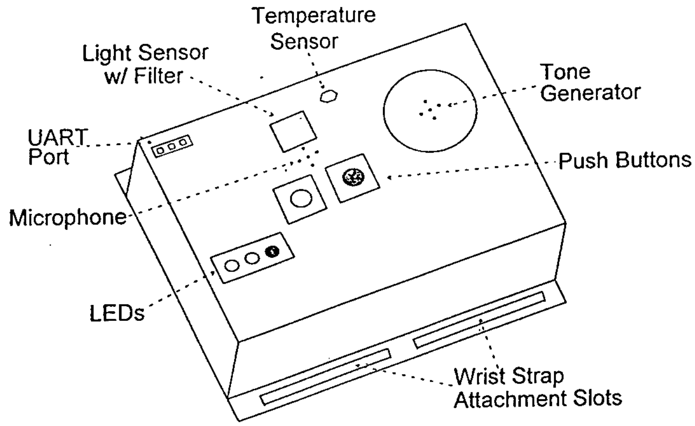

Figure 2. Schematic drawing of the USARIEM vigilance monitor.

and mental state. One of the chief capabilities of these devices is the ability to assess vigilance, although other types of cognitive performance can also be continuously monitored in the field. They also can be programmed to evaluate various types of data they acquire and, based on these data, intervene to modify certain types of behavior, including mental performance. As discussed above, it appears that activity data collected by actigraphs can be correlated with more direct measures of performance; however, actigraphs cannot measure any type of performance directly. Therefore, a direct, continuous performance assessment capability would be particularly useful in many applied studies.

The USARIEM monitor, shown in Figure 2, can simultaneously measure patterns of rest and activity like actigraphs, several key environmental factors, and vigilance, a key behavioral parameter discussed below. Like state-of-the-art activity monitors, the device records continuously and stores data in onboard memory for later retrieval. The device contains the equivalent of a first generation personal computer, including 128 kilobytes of memory, and an eight-bit microprocessor. It also has substantial signal processing capabilities and simple auditory and visual output capabilities. It will record continuously for more than five days. Figure 3 presents data recorded by the monitor over four days

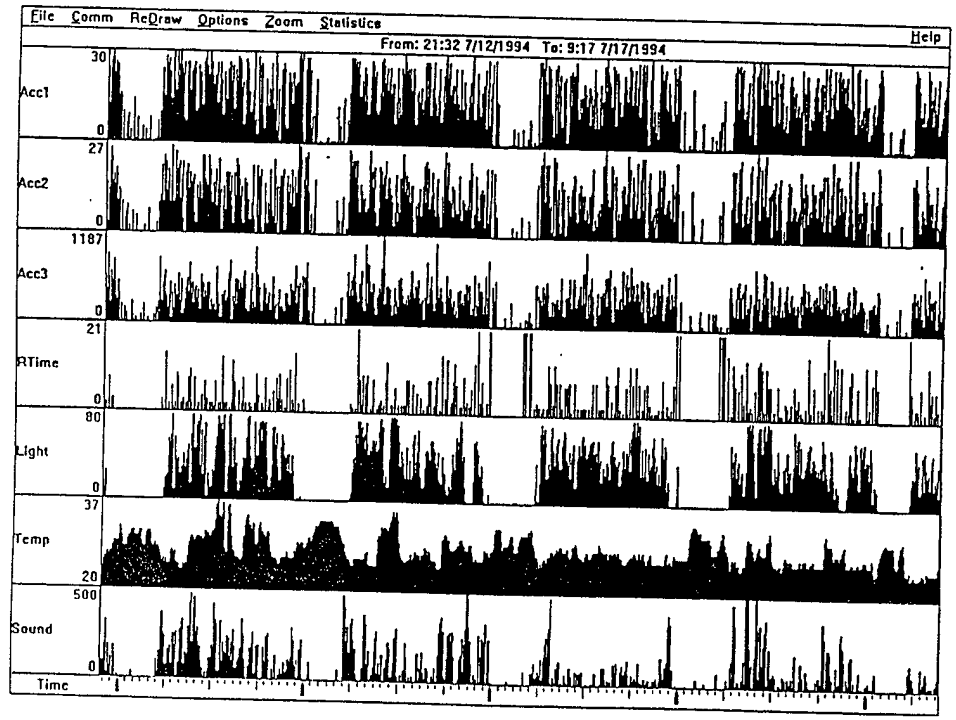

Figure 3. Data collected with the USARIEM vigilance monitor for four consecutive days in the field. The top three channels, Acc1 through Acc3, represent activity data collected with different sensor sensitivities. The fourth channel, labeled Rtime, displays the responses of the subject to the presentation of a sequence of tones at random intervals. The height of each bar represents the speed of response to the tone. The channel labeled Light is the illumination level recorded at the wrist of the subject. The Temp channel continuously records ambient temperature levels and the last channel records sound levels in arbitrary units.

by a subject in the field. As configured for that study, seven channels of data were simultaneously acquired, including three channels of activity data, a vigilance/reaction time channel, light, sound, and ambient temperature. The device can be worn on the wrist, although it is somewhat larger than state-of-the-art activity monitors such as the AMA-32. It is programmed and the data it records are retrieved via an RS-232 interface to any IBM-compatible personal computer. It should also be noted that because the monitor contains a user programmable microcomputer, it can be used not only to assess vigilance but to actively intervene, if desired, to prevent degradation in performance of the wearer.

Vigilance—A Key Indicator of Alertness

Given the ability to assess performance in the field by using the USARIEM monitor, the question of what specific behavioral parameter to measure is critical. The selected task not only must be operationally relevant but also must be simple enough to perform on a frequent basis without disrupting the daily activities of the wearer.

Vigilance is one behavioral parameter that can be easily measured and is an important determinant of many key aspects of military performance. There are a wide range of behavioral parameters that are critical for soldiers as they conduct their missions. However, maintaining vigilance is particularly important for many key military duties. Vigilance can be considered to be the ability to remain alert and to focus attention on relevant environmental stimuli. It is essential that soldiers maintain vigilance under the worst circumstances, such as when they are sleep deprived, when they are at the nadir of the circadian performance rhythm (in the middle of the night or early morning), and when they are physically and environmentally stressed. If a key sentry, an operator of surveillance equipment like radar, a truck driver, or a helicopter pilot cannot maintain vigilance, the consequences can be catastrophic. Vigilance deteriorates even in well-rested individuals, if it must be sustained for long periods of time (32).

Vigilance is of great practical significance, since a wide variety of key civilian and military tasks, such as operation of motor vehicles and industrial equipment, requires sustaining it for long periods of time (33). A number of accidents, such as the near catastrophe at the Three Mile Island nuclear reactor, and commercial aircraft crashes have been attributed, at least in part, to the failure of human operators to detect critical stimuli (34, 35). It has also been suggested that vigilance tasks may be more relevant to the performance of everyday activities than the briefer tests of cognitive performance typically employed in cognitive test batteries (32). Vigilance tasks are sensitive to the effects of many factors on human brain function including sleep loss, drugs, hormones, food constituents, and a variety of environmental factors (4, 32, 36, 37, 38, 39). Also, there are substantial data relating vigilance to real world performance including marksmanship, sentry duty, and driving (40, 41). Given the operational importance of vigilance and its sensitivity to nutritional and other variables, we selected it and reaction time, a closely related parameter (42), as the behavioral functions of greatest relevance to assess in the field with our new ambulatory monitor.

In an effort to determine whether the new monitors will be useful in a variety of field settings, we have initially employed them in concert with more conventional performance and environmental assessment technologies. In the studies described below, the monitors were employed not as a primary dependent measure but to determine whether they would perform adequately and reliably in the field, and to collect preliminary information regarding possible utility of the new device. Previously, when introducing new ambulatory monitoring technologies, there have been significant reliability issues until adequate procedures for field use were developed (6, 7). Development of well-defined, user-friendly software for programming the device and reliably retrieving data is also essential.

Continuous Assessment of Vigilance

The unique capability of the USARIEM monitor is its ability to continuously assess performance in the field. Although numerous field studies have been conducted in which performance is assessed, the technical and operational constraints have greatly limited the nature and quality of the data collected. The new technology we have developed permits the investigator to continuously monitor mental performance when test subjects are at a remote or dangerous site and are inaccessible to the scientist. Furthermore, since the monitors can simultaneously collect information on key environmental variables, performance data collected in the absence of the investigator can more readily be interpreted. By knowing the overall activity level of the subject, his patterns of sleep, and the extent and timing of strenuous physical activity, vigilance or other types of behavioral data collected by the monitor can be placed in the context of the test subject's activities during the course of the study. Generally, when laboratory behavioral studies are conducted, investigators attempt to control as many extraneous variables as possible. Often illumination levels and background sound are controlled, and ambient temperature is regulated. It is not possible to control these parameters in the field, but quantitative information on them can be gathered by the USARIEM monitor and knowledge of how they may interact with performance should enhance the ability to conduct and interpret nutrition and many other types of field studies.

Since the USARIEM monitor can generate both auditory and visual stimuli, a wide range of relatively simple behavioral tests could be conducted in the field with it. Configuring a device for continuously assessing performance in the field poses unique challenges to the investigator. The nature and frequency of the test or tests to be administered must be weighed. Although frequent assessment of performance is highly desirable, the intrusiveness of the task on the wearer's daily activities must be carefully considered. In addition, the actual task must be selected to yield as much relevant data as possible. As discussed above, vigilance and reaction-time tasks have been found to be among the most useful in describing an individual's performance and in detecting the effects of a wide variety of experimental treatments including various nutritional treatments, environmental stressors, sleep loss, and pharmacologic compounds (2, 5, 21, 32, 36, 42, 43). Therefore, in our initial studies employing the USARIEM monitor, we focused on these types of relatively simple but important types of cognitive performance. We have also focused on vigilance and reaction time, since changes in these parameters have direct implications on the ability to perform a variety of key military duties, such as monitoring communications, operating vehicles, and standing sentry duty. Many critical civilian occupations also require optimal vigilance and related types of performance as noted above (2, 34).

Field Studies with the USARIEM Vigilance Monitor

We first evaluated the performance assessment function of the USARIEM monitor during a field study conducted in a temperate climate. As configured for that preliminary evaluation, the monitor assessed the vigilance of the wearer continuously except during periods of sleep. Figure

3 presents the data recorded from one subject during that field study: the channel labeled RTime represents the behavioral data collected during the four days of the study. During that period, at random intervals once every 15 minutes, the monitor's speaker presented a short duration tone. The subject was asked to respond by pushing a small switch on the monitor as soon as he heard the tone. If the subject did not respond to the initial tone, a second louder tone was presented 6 seconds later. Finally, a third still louder tone was presented 11 seconds after the first tone if the subject still failed to respond. If a total of 20 seconds elapsed from the first tone without a response by the subject, the monitor recorded the stimulus sequence as missed. In addition to determining whether or not the subject responded to the tones, the monitor also recorded the time required for the subject to respond (reaction time). Figure 4 presents daily patterns of response to the tones by one subject on days 1 and 4 of the study. Generally the subject responded to most tone sequences, although there were a few instances of nonresponding (indicated by a reaction time of 20 seconds). In spite of the requirement to continuously respond over the course of the four-day study, on the final day the subject was still responding to the majority of the stimuli, although there appeared to be some degradation in performance from day 1 to day 4. This decrement over the four days may represent the chronic effects of fatigue associated with sleep loss in the field. Figure 5a presents sleep time each night estimated using the activity channels of the monitor. During the field exercise, the subjects only slept about five hours a night, so it is possible that the cumulative effects of the sleep loss, in combination with disrupted sleep that typically occurs in the field, may produce subtle decrements in vigilance and reaction time (Fig. 5b).

In a second study, the monitor was used to assess performance of Navy SEALS who received a single dose of 200 milligrams of caffeine or placebo prior to testing. In that study, the subjects wore the monitor while they were conducting a training exercise in small boats. The volunteers in the study were trainees in the Navy SEAL program, a high-intensity, physically and mentally demanding course designed to train elite commandos (44). The monitors were used to assess vigilance and reaction time while the volunteers were inaccessible to the investigators and were subjected to substantial physical and thermal (cold) stress (Fig. 6). We have previously shown that vigilance and reaction time are sen-

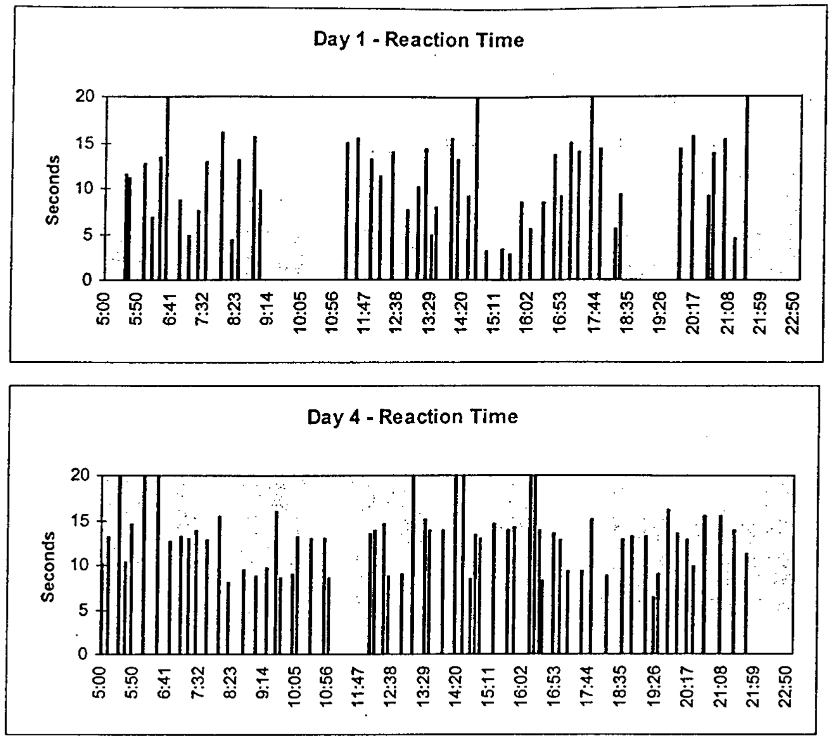

Figure 4. Vigilance and reaction time data collected by the USARIEM vigilance monitor from one individual on days 1 and 4 of a field study. The latency of responding to the presentation of a sequence of up to three tones is indicated by a vertical bar. The height of each bar represents the speed of response to the tone.

sitive to the effects of low and moderate doses of caffeine (4, 5). Figure 6a illustrates differences in reaction time in SEAL trainees who received caffeine or placebo. The reaction time of subjects receiving caffeine was faster than those receiving placebo. Caffeine also appeared to increase the probability of responding to the auditory stimuli emitted by the monitor (Fig. 6b). These preliminary findings will need to be replicated with larger groups of subjects before the usefulness of the USARIEM monitor to assess performance is adequately documented.

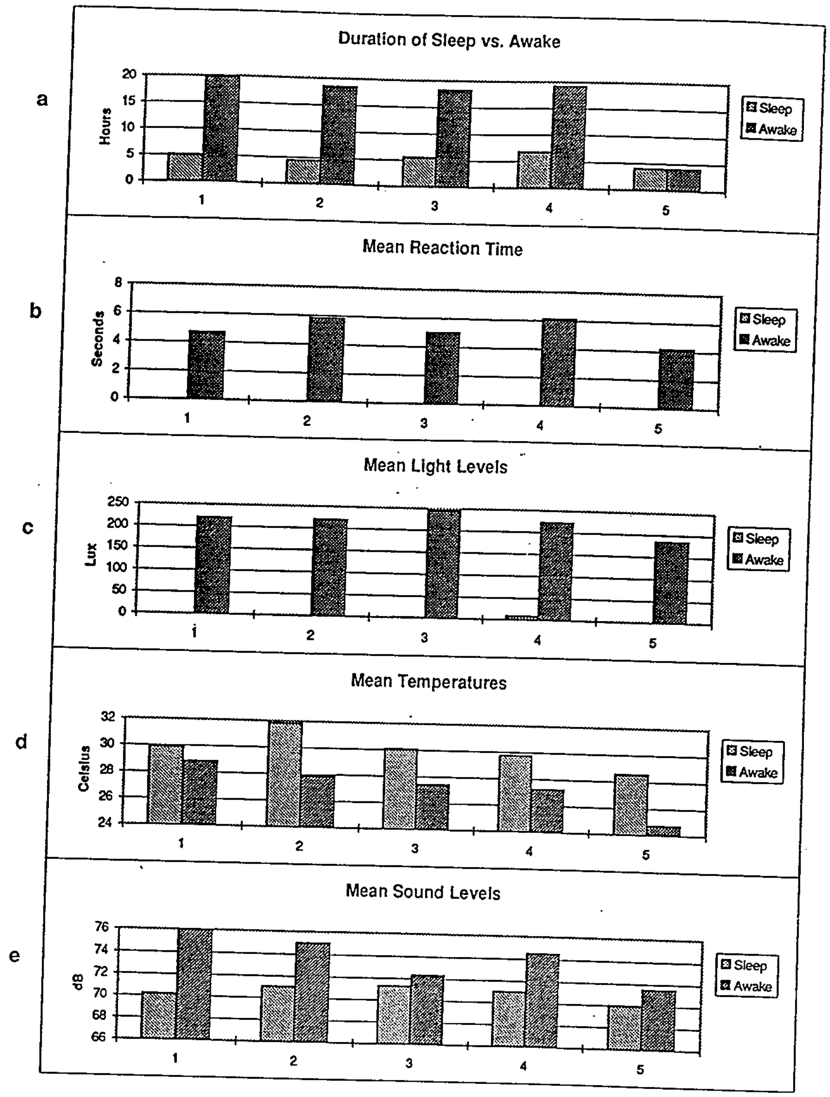

FIGURE 5

Figure 5. Estimated sleep, reaction time, light levels, temperature, and ambient sound over the course of five days in the field. The data are classified into sleep and waking periods based on patterns of activity.

Motor Activity

As discussed above, the continuous assessment of motor activity is a valuable technique for gathering information about sleep, circadian rhythms, and energy expenditure of the wearer. Activity data are particularly valuable in field studies, since it is often difficult to gather any other form of information regarding the timing of specific duties or other activities in the field. The monitor we have developed can acquire multiple channels of activity data simultaneously, unlike the single channel capability of commercial activity monitors. The individual activity channels can be programmed to differ in their function and recording characteristics. For example, several channels might be selected to be sensitive to lower amplitude activity whereas others might be sensitive to moderate or high amplitude accelerations. Channels can also vary with regard to their temporal characteristics, so that differences in the duration of motions emitted by the wearer can be assessed.

As discussed above, Figure 3 displays four days of data collected in the field using the USARIEM monitor. Data from three channels of activity data, in counts per minute, are presented in the first three panels (Acc1–Acc3). Although in this application only three channels are recorded simultaneously, the device has the capability of simultaneously recording more than sixteen different channels of activity data. Channels 1 and 2 (Acc1 and Acc2, Fig. 3) vary with regard to amplitude of the acceleration they will sense, whereas Channel 3 (Acc3) has a longer time constant, so it will be more sensitive to longer duration accelerations. These variations in recording characteristics are achieved by changing the internal sensitivity of the sensor in the device, not by using multiple sensors. We believe that the capability to simultaneously record a variety of different channels of activity will, among other things, permit the development of improved algorithms to predict sleep versus waking state, as well as improve the ability of monitors to predict energy expenditure. The additional data acquired by the multiple channel technique for activity assessment should more fully describe the individual's behavior by providing quantitative information on the minute-by-minute characteristics of an individual's activities, not just total counts of activity as currently provided by available actigraphs. As noted above, data from actigraphs have been used to estimate energy expenditure, although there are substantial limitations to the technique (15, 16). Some studies

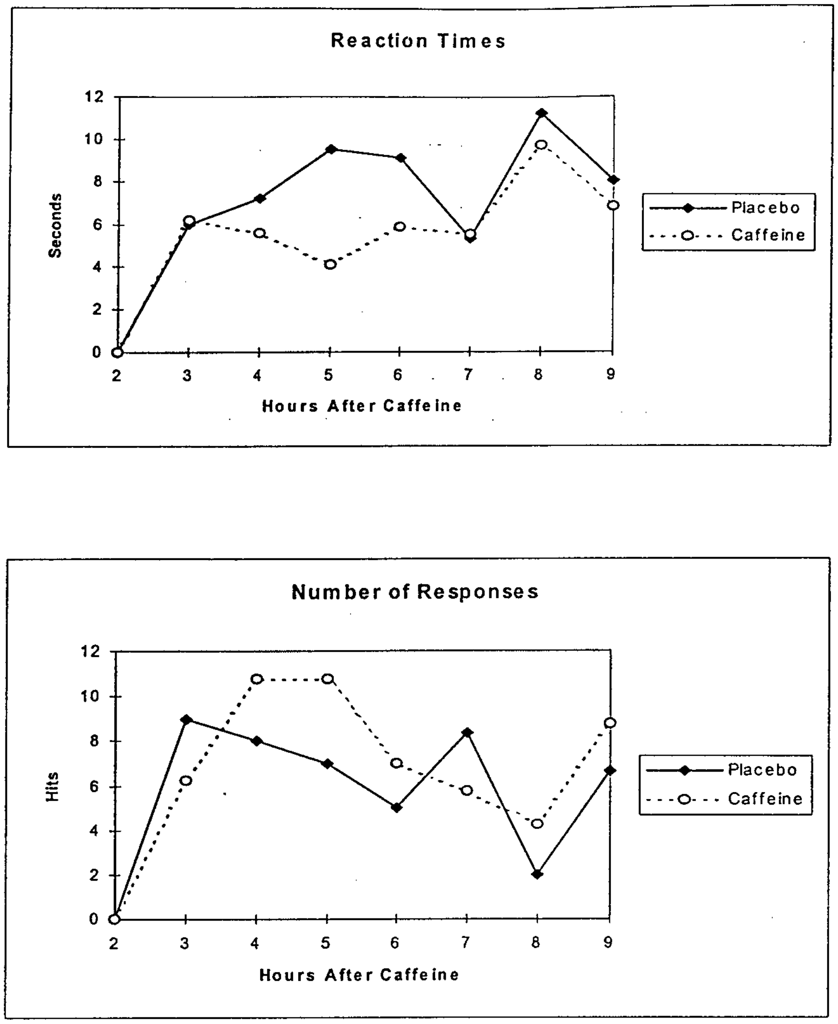

Figure 6. Mean reaction time (top) and number of correct responses (bottom) to presentation of auditory stimuli (tones) by Navy SEAL trainees during a one-night training exercise conducted in small boats and on shore. Half the subjects received placebo and half received 200 mg of caffeine (N=8).

have documented substantial agreement in energy expenditure assessed with actigraphs and more traditional measures of energy expenditure such as oxygen consumption (16). By simultaneously collecting information from multiple channels varying in regard to their recording characteristics, more accurate estimation of energy expenditure may be possible, since a more complete description of the physical activity of the wearer will be obtained.

In the SEAL caffeine study described above, we also programmed the monitor to assess motor activity. Figure 7 presents mean activity counts for three channels of activity data acquired simultaneously during the night of that study when the volunteers were engaged in a high-intensity training exercise. The three channels of activity varied in the same manner described above—Channels 1 and 2 (Acc1 and Acc2) vary with regard to amplitude of the acceleration they will sense, whereas Channel 3 (Acc3) has a longer time constant. During the assessment period, the SEAL trainees were usually engaged in heavy physical activity with interspersed periods of behavioral testing, rest, and meal time. Different patterns of response across the different channels are readily apparent, indicating that different activities do have characteristic signatures. There was substantial variation across the three channels with the greatest differences occurring between the low frequency channel and the two high frequency channels. The correlation between Channel 1 and 2 was 0.917, the correlation between Channel 1 and 3 was 0.735, and between Channel 2 and 3 was 0.614. Whereas it is unlikely that it will be possible to determine precisely what activity an individual is engaged in based on activity records, these preliminary data suggest that it will be possible to more readily distinguish different classes of activity if multiple channels of activity are acquired, and presumably also to more accurately access energy expenditure.

There are, of course, a multitude of environmental and other factors regulating human behavior. Many cannot be directly assessed but several can be acquired automatically with minimal difficulty due to the availability of miniature low power sensors. Therefore, we have included several environmental sensors in the device we have developed.

Ambient Sound

One key environmental factor influencing human rest, activity, and other behaviors is the pattern and level of sound in the environment. To the

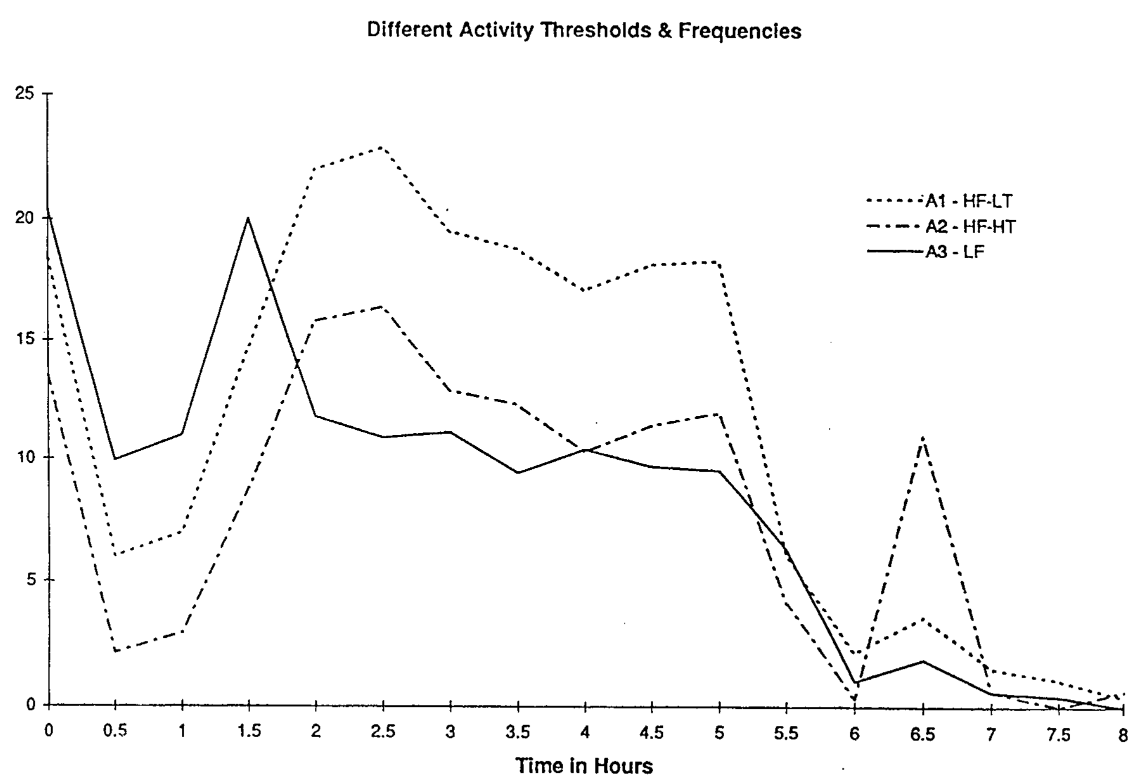

Figure 7. Activity data collected from one subject in the SEAL field study. Activity counts for each channel are plotted separately over the eight hours of the study. The line labeled HF-LT is the high frequency, low threshold channel. The line labeled HF-HT is the high frequency, high threshold channel. Line LF is the low frequency channel.

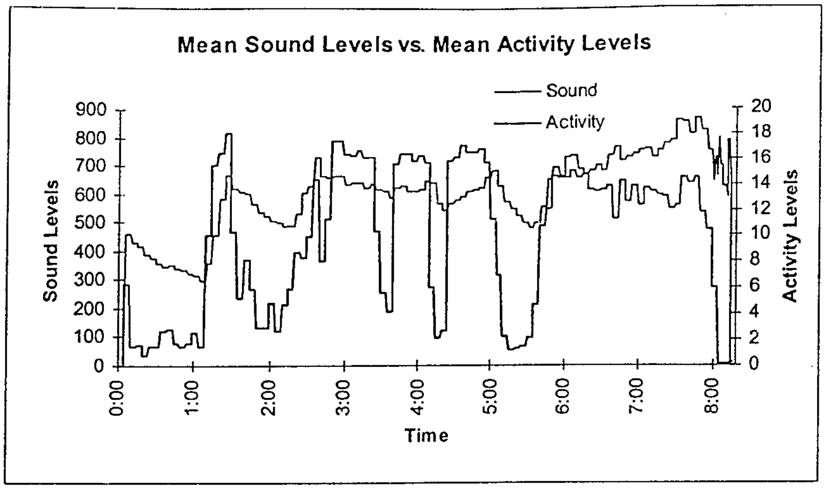

Figure 8. Mean ambient sound and activity levels from eight subjects participating in the SEAL study. The data are presented in five-minute time blocks.

best of our knowledge, ambulatory studies investigating the relationship of ambient sound levels and human behavior patterns have not been conducted because of the lack of suitable devices to simultaneously assess both parameters. Humans are sensitive to a wide variety of auditory stimuli, and loud or even moderate volume sounds can severely disrupt sleep. The USARIEM monitor has a miniature microphone mounted inside, and information on background sound levels the wearer experiences can be continuously monitored. The monitor does not have the capability to record sound like a tape recorder but rather, at regular intervals, saves information on ambient sound intensity levels in its onboard memory. Therefore, the information it gathers indicates the background sound intensity levels to which the wearer is exposed at each recording interval. Because the USARIEM-developed device simultaneously records environmental conditions and activity patterns, it is possible to determine how ambient patterns of sound relate to the activity of the wearer. Figure 8 presents data collected during the previously discussed SEAL study. Over the course of the night of testing, there appears to be a relationship between periods of reduced activity and ambient sound levels, although the relationship is not a strong one. As would be expected, periods of lower sound intensity levels appear to be somewhat correlated with periods of lower activity. However, in a longer duration field study, conducted over several days, a clear relationship between ambient sound and activity can be observed (Fig. 5). When a subject wearing a monitor in this study was sleeping, as defined by continuous periods of very low activity, ambient sound levels were much reduced (Fig. 5a and 5e).

The availability of minute-by-minute information on quality and quantity of sleep and simultaneously recorded ambient patterns of sound may be useful in predicting sleep and in developing appropriate strategies to increase the restfulness and extent of sleep in the field. Sound intensity levels clearly affect sleep and performance (45). Active or passive techniques to provide an appropriate sound environment for sleep should be part of an overall sleep management program (see Comperatore, Lieberman, Kirby, and Allan, "The Efficacy of Melatonin as a Component of the Crew Endurance Management System During Army Aviation Missions" herein). Furthermore, as we more fully describe the environment in which soldiers in field studies operate, more detailed understanding of factors regulating performance may be possible.

Ambient Illumination

Bright light is a key factor regulating human rest and activity cycles and the circadian rhythms underlying these behaviors. It was not until a few years ago that the critical nature of bright light in the regulation of human circadian rhythms and performance became known (46). The overall direct effects of bright light on human performance are controversial (46–49), but certain key military tasks such as marksmanship and sentry duty are directly dependent on lighting conditions. Given the importance of light in regulating behavior, we have included a light sensor in the USARIEM monitor so that information regarding the duration and amplitude of individual exposure to light can be continuously acquired (Fig. 3; Channel 5 [Light]).

Individual variations in light exposure and their effects on circadian rhythms and performance in the field have not been thoroughly investigated. In a study conducted at Camp Parks, California, with medical reservists as test subjects, we collected data using the USARIEM monitor and also a stationary weather station with an onboard radiometer. Figure 9 presents data on mean ambient exposure to light from four reservists and also from the weather station's onboard light sensor. The

Light Levels - Camp Parks

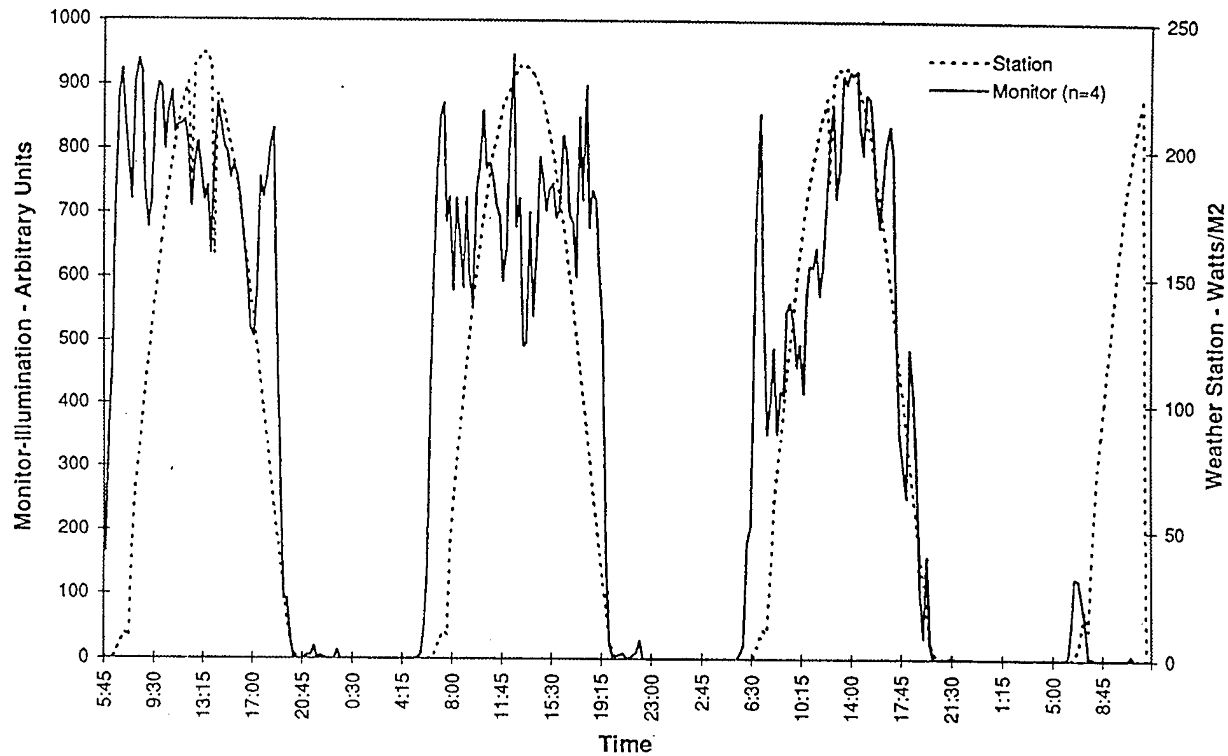

Figure 9. Ambient light levels during the Camp Parks field study. Ambient light levels were recorded on the wrists of four subjects and the mean value derived. Weather station data were concurrently recorded at the site by a stationary device.

USARIEM monitor appears to have accurately tracked ambient illumination. Interestingly, daily patterns of light exposure of the volunteers appeared to be much more variable than ambient conditions and also rose earlier in the morning and fell later at night, perhaps an indication of exposure to artificial sources of light in the morning and evening. The ability to monitor illumination levels (particularly in studies of circadian rhythms and sleep) should provide information on a potentially confounding factor, as well as helping the investigator to describe the milieu in which the individual is operating. Furthermore, understanding the pattern and intensity of light exposure in operational settings will permit formulation of appropriate intervention strategies to improve operational effectiveness as discussed elsewhere in this volume (see Comperatore, Lieberman, Kirby, and Allan, "The Efficacy of Melatonin as a Component of the Crew Endurance Management System During Army Aviation Missions" herein).

Temperature

Although the importance of ambient temperature in regulating behavior is well documented, the pattern of ambient temperature to which an individual is actually exposed is difficult to obtain. Extreme heat or cold will have substantial effects on a wide range of behaviors, including activity, sleep, and physical and mental performance. The effects of subtle variations in climate are more difficult to measure, but obviously humans go to great lengths to regulate the ambient temperature they experience. Therefore, the USARIEM monitor includes a thermistor, which continuously assesses ambient temperature on the surface of the monitor (Fig. 3, Channel 6 [Temp]). Although ambient temperature is not the only environmental factor modulating thermal status of an individual, it clearly is an important factor. In field studies it is often difficult to obtain reliable information on ambient temperature conditions to which soldiers are exposed. Furthermore, even when climatic data are available, they do not describe the conditions an individual soldier experiences, but rather the conditions at a stationary weather station (50).

In the study conducted at Camp Parks as discussed above, large variations in individual exposures were objectively documented with the USARIEM monitor as shown in Figure 10. The differences in individual temperature exposures in the relatively constrained environment of

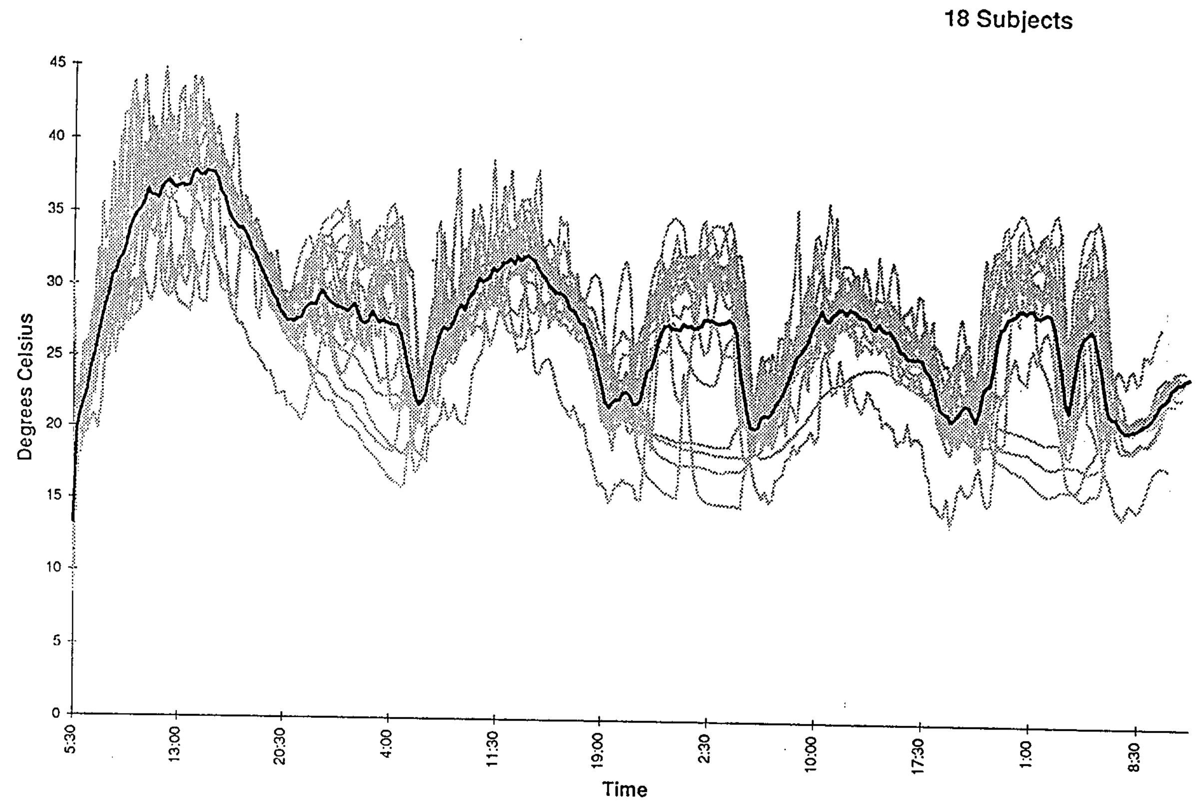

Figure 10. Mean and individual temperature exposures during the Camp Parks field study. Data from individual monitors are plotted in gray. Mean temperature levels are plotted in black (N=18).

Camp Parks, where the test subjects were rarely more than several hundred meters apart, were greater than 25°C. In that study, reservists from a medical unit were training in central California in the summer and several instances of heat illness were observed. In the Camp Parks study, in addition to recording individual temperatures with the USARIEM monitor, the stationary weather station also recorded air and ground temperature. Figure 11 presents both weather data and mean temperature exposures in four subjects. The patterns of thermal exposure recorded by the monitor follow the daily fluctuations in air temperature each day but appear to be significantly damped, particularly with regard to the higher daytime temperatures recorded. Interestingly, it also appears that the lowest temperature individuals experienced occurred at dawn and dusk (Fig. 11).

The USARIEM monitor, by allowing for continuous individual temperature monitoring on each subject participating in a study, may permit more accurate tracking of environmental exposures, particularly when weather station or similar data are also available. Furthermore, individual susceptibility to environmental stress may be related not only to overall climatic conditions but also to the individual's actual exposure and activity patterns. Differences in the microenvironment an individual is exposed to can have dramatic effects on actual levels of environmental stress. In a hot environment, a soldier working in the sun will have a much greater risk of heat illness than another soldier in the same unit who is manning an underground communications bunker.

Activity levels of soldiers and ambient temperature are also likely to be related in the field. The U.S. Army provides specific formal guidance to unit leaders that requires them to regulate the activity of soldiers in potentially dangerous thermal environments. In addition, the individual soldier may either consciously or unconsciously modify his daily patterns of activity and circadian rhythms to adjust for thermal load. In several studies, we have observed that at night or when soldiers or sailors are attempting to rest, ambient temperatures we record on their wrist monitors are higher than during periods of activity. Although somewhat counterintuitive, particularly if the ambient environment is hot or temperate, we have observed such a relationship on several occasions. It is worth noting that during sleep, human core body temperature declines and individuals may be attempting to conserve heat when at rest by adapting behavioral strategies such as sleeping under a blanket or

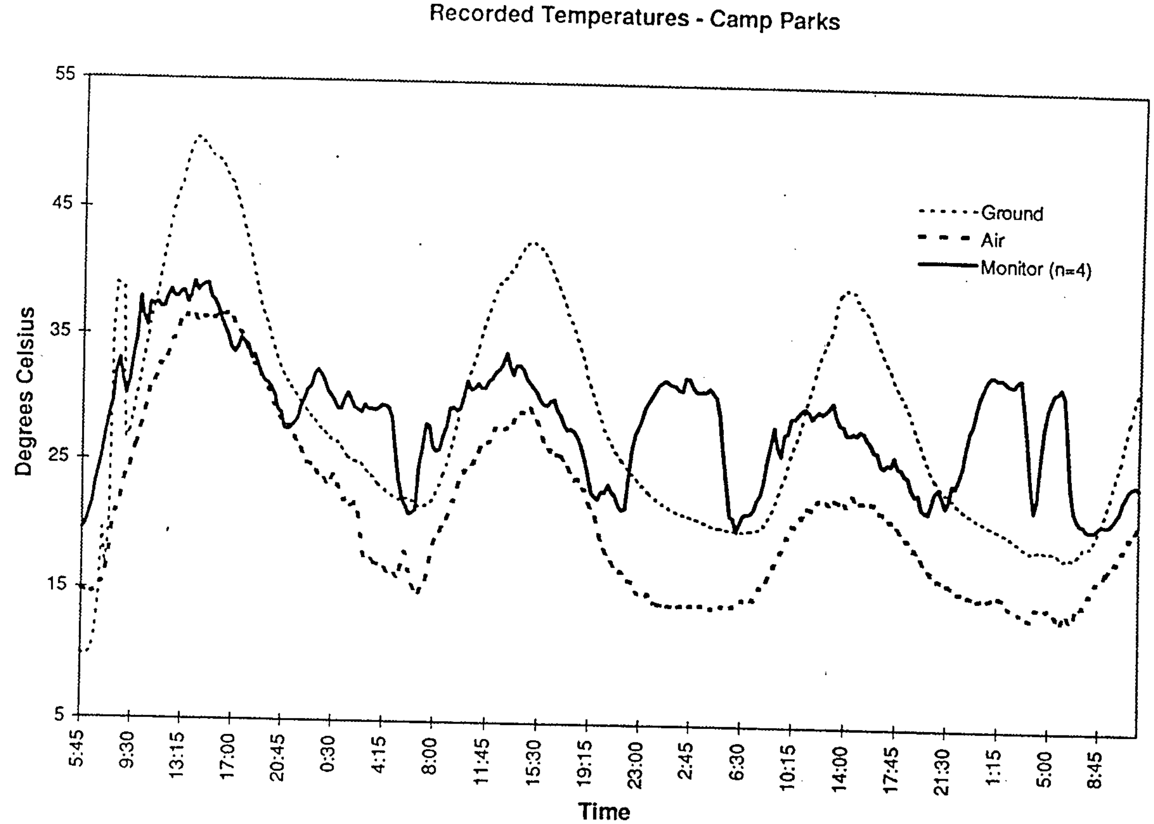

Figure 11. Mean temperature data from four subjects in the Camp Parks field study plotted with ground and air temperature simultaneously recorded by the weather station.

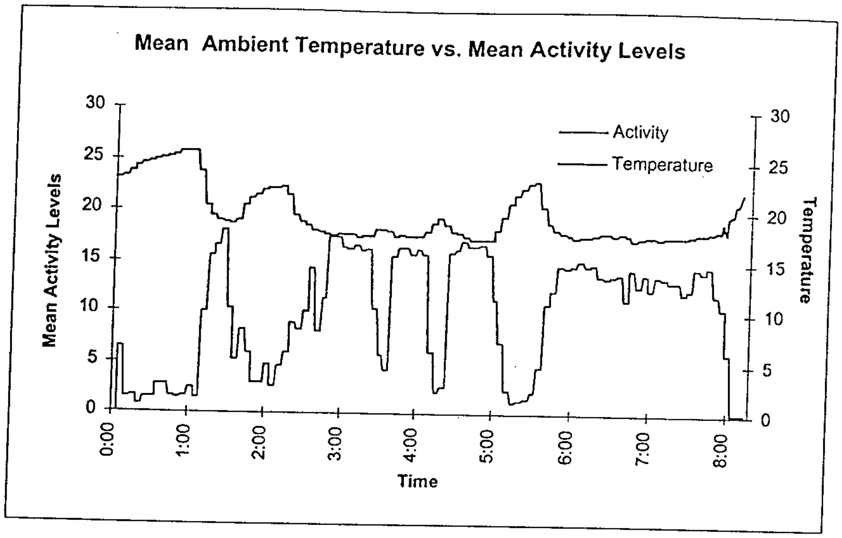

Figure 12. Comparison of changes in mean activity level and ambient temperature over several hours.

huddling together. We observed both types of this behavior in different studies. At Camp Parks, soldiers slept under blankets or in sleeping bags, and recorded temperatures rose at night (Fig. 11). In the SEAL study discussed above, the trainees huddled together under their boats whenever they had the opportunity to rest. The trainees were operating in a wet environment, so even though ambient temperatures were moderate, there was substantial cold stress. Therefore, the increased ambient temperature we consistently observed when they had the opportunity to rest (Fig. 12) was not very surprising.

Conclusion

Based on the success of actigraphs in providing scientists with a new, unique tool for understanding human behavior, we have attempted to design and fabricate a device for applied and basic studies of human performance in the field. The device we have developed can also be used to investigate the relationship between various environmental factors, performance, and patterns of rest and activity. The USARIEM vigilance monitor has a number of unique capabilities. In addition to assessing vigilance and reaction time, it continuously acquires information on key environmental factors such as ambient illumination, sound level, and temperature. Since recording spontaneous motor activity has proven be so valuable, the device also records multiple channels of this parameter.

When wearing the monitor, the subject can continue with most daily activities, unlike conventional cognitive performance assessment technologies. Of course, it will still interfere somewhat with ongoing duties but compared with halting all activities to take a behavioral test, responding to it is a minor inconvenience.

There is a definite need for innovative technologies that can be employed to assess human performance and other aspects of behavior in the field. In laboratories like USARIEM, where the mission is to sustain and enhance soldier performance, such technologies should assess behaviors of clear relevance to the duties of soldiers and other war fighters. Of course, these emerging technologies can also readily be applied to a variety of applied and basic civilian research issues.

Disclaimer

The views, opinions, and/or findings in this report are those of the authors and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other official documentation. Human subjects participated in these studies after giving their free and informed voluntary consent. Investigators adhered to AR 70-25 and USAMRDC Regulation 70-25 on the use of volunteers in research. Citations of commercial organizations and trade names in this report do not constitute an official Department of the Army endorsement or approval of the products or services of these organizations.

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13. ABSTRACT *(Maximum 200 words)*

The ability to assess mental and physical performance, in an automated and minimally intrusive manner, is critical for the conduct of military field studies and applied research in nutrition, neuroscience, and environmental and occupational medicine. Technologies that are currently available for automated field assessment of performance are limited, and commercially available methods for ambulatory monitoring, such as the activity monitor (actigraph), do not directly assess any aspect of performance. This paper will introduce a new device, the U.S. Army Research Institute of Environmental Medicine vigilance monitor, which was developed for assessment of human performance in an automated, continuous manner in the field. The monitor has evolved from the actigraph and from microcomputer-based tests of cognitive function. The device continuously monitors and records certain aspects of human performance and, like the actigraph, patterns of activity of the wearer. The device assesses vigilance and reaction time by presenting auditory stimuli and by assessing the wearer's responses. In addition, the USARIEM vigilance monitor continuously assesses a variety of environmental conditions that are of relevance to the mental and physical performance and health of the wearer such as: ambient illumination, sound, and temperature. The device is small enough to be worn on the wrist or belt and, like the actigraph, is completely self-contained, requiring no external input to perform all of its functions for several days. Preliminary data from several military field studies employing the device will be presented, and some of the implications of this new assessment technology will be discussed.

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